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13 ABSTRACT(MAX 200 WORDS) THIS PAPER EXAMINES CRITICAL ISSUED IN THE RESPONSE OF AMMUNITION MATERIALS TO DYNAMIC LOADING. THE PAPER DISCUSSES THESE ISSUES IN TERMS OF THE FUNCTION OF AMMUNITION MATERIALS AND THEIR REQUIREMENTS FOR SAFE LAUNCH, IN-FLIGHT PERFORMANCE AND TERMINAL EFFECTIVENESS. DEFICIENCIES IN MATERIAL CHARACTERIZATION AND APPLICATION ARE HIGHLIGHTED.

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RESPONSE OF AMMUNITION MATERIALS TO DYNAMIC LOADING

N.M. BURMAN, D.S. SAUNDERS, B.E. WALSH and R.L. WOODWARD

Department of Defence
Defence Science and Technology Organisation
Materials Research Laboratory,
P.O. Box 50 Ascot Vale Vic. 3032

SUMMARY This paper examines critical issues in the response of ammunition materials to dynamic loading. The paper discusses these issues in terms of the function of ammunition materials and their requirements for safe launch, in-flight performance and terminal effectiveness. Deficiencies in material characterisation and application are highlighted.

1. INTRODUCTION

Some of the non-explosive components of ammunition are typically subjected to extremes of stress, dynamic loading rate and temperature. Component properties required to survive these conditions, which include high melting point, strength, toughness and durability, necessitate the almost exclusive use of metallic materials. Ammunition components may be classified in terms of their function, i.e., **launch** - (cartridge cases and rocket motors), **response to high explosive or impact loading** - (bombs, HE shell, HESH or HEP, shaped charges, mines and demolition and special operation devices, armour piercing, practice ammunition) and **components** - (primers, fuze and assembly components, structural and guidance elements). The range of conditions applied to these components during both their manufacture and final utilisation requires judicious materials selection, based on a sound knowledge of dynamic materials properties, to ensure both safe use and optimised terminal effectiveness.

Because of the often conflicting materials property requirements, as well as the purely physical limits of the materials, ammunition design is commonly a compromise between the exigencies of environmental stability, safe handling, reliable launch (launch safety), flight characteristics and functioning at the target. The typical responses to dynamic loading which limit ammunition performance are reviewed in relation to materials, design, manufacturing and cost effectiveness considerations.

2. STORAGE AND TRANSPORT

Although the storage, transportation and handling of high explosive filled munitions rarely produce extremes in dynamic loading, materials defects generated during this phase can severely reduce a munition's ability to successfully withstand the more severe load conditions encountered during launch and/or target interaction. Failure of the munition to function correctly at either launch or at the target constitutes a severe safety hazard to friendly forces.

With the introduction of lower toughness steels in the new generation HE artillery projectiles, the problem of rough handling has been highlighted [1]. It is possible that, due to the high stresses developed at specific locations in the projectile wall during rough handling, manufacturing flaws can grow or small cracks can be introduced. Typical rough handling and drop tests for artillery projectiles are shown in Figure 1.

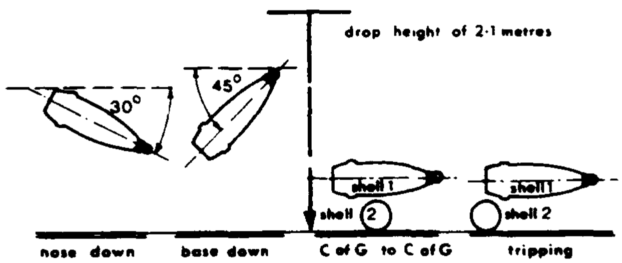


Figure 1. Typical rough handling and drop tests for artillery projectiles.

Defects developed during rough handling may grow catastrophically under launch conditions, as discussed below. In the early 1970s, a very low fracture toughness steel, which promised markedly improved projectile terminal performance, was investigated. However, it was soon discovered that projectiles manufactured from this steel required highly conservative handling methods to reduce the risk of inducing defects before launch. Slightly tougher steels and appropriate heat treatment methods assure reasonable handling safety of HE

projectiles.

Stress corrosion cracking of certain Al alloy LAW rocket motor cases and end closures under storage has resulted in the premature failure of these components at launch [2]. In these cases, the critical cracks were found to be extremely small and difficult to detect after manufacture. Newer Al alloys and heat treatments provide greater resistance to stress corrosion cracking and inherently higher fracture toughness and lower yield strength levels. These modifications have been introduced into service weapons, and although the component changes have incurred some weight penalties, these have been largely overcome by the use of new propellants.

To further reduce the incidence of pre-launch cracking, considerable progress has been made in the safe handling and transport of ammunition due largely to improvements in packaging technologies.

3. LAUNCH

Munitions may be broadly divided into those which experience relatively low launch stresses (e.g. aircraft bombs and cluster munitions), and those which experience high launch stresses such as projectiles launched from high velocity guns or high pressure rocket launchers. The typical range of strain rates and loading levels involved with each type of munition is illustrated in Table 1.

Munitions which are launched under conditions of high strain rate and loading levels are found to be most sensitive to the presence of manufacturing defects (e.g., heat-treatment induced cracks and score marks). Such defects may propagate rapidly under the dynamic stresses imposed by launch, and this can give rise to failure or premature detonation of the munition. Important developments in recent years have been in sabot and KE penetrator designs capable of achieving the stable launch of high length/diameter (L/D) ratio penetrators at increasing velocities [3-5]. Similarly, artillery projectiles incorporating steel casings with improved fragmentation performance have been developed despite early problems with rough handling and launch safety.

To assure launch safety, considerable experimental work has been undertaken on the development of techniques for measuring the fracture toughness of forgings and finished projectiles [6-9]. This work, in conjunction with stress analysis and the application of fracture mechanics methodologies to artillery projectiles [10,11], allows the prediction of critical crack sizes at most locations in the walls of the projectiles. Figure 2 shows the axial stresses developed in an M107 artillery projectile on launching. From these analyses it is possible to specify minimum fracture toughness values and NDI requirements for production HE projectile casings. In order to obtain fracture toughness data, a range of specimen designs and test methodologies have been developed and applied to specimens taken from artillery projectiles as illustrated in Figure 3.

Typical fracture toughness data for artillery projectile steels are given in Table 2. Using calculated launch stress (an example of axial stresses is shown in Figure 2) and knowing the crack geometry at specific locations in the shell [1,10], predictions of critical crack sizes (depth) can be made. This example shows how increasing fracture toughness significantly increases critical crack size in the projectile walls. The table highlights the sensitivity of critical crack size to fracture toughness.

Table 1
Strain Rate and Loading Levels for Carriage and Launch of Munitions.

Method of Launch	Munition Type	Loading Level g
Propellant	HE Projectile Mortar APFSDS Bullet	8,000 - 20,000 (launch) 3,000 - 4,000 (launch) 50,000 (launch) 80,000 (launch)
Rocket	LAW Ground-Air Ship-Air Air - Air	4,000 (launch) 9 -10 (manoeuvre) 5 - 10 (launch)
Electromagnetic (Rail Gun)	"Bullet"	60,000 - 100,000 (launch)
Platform (Aircraft Launched)	Bomb	1 (launch)

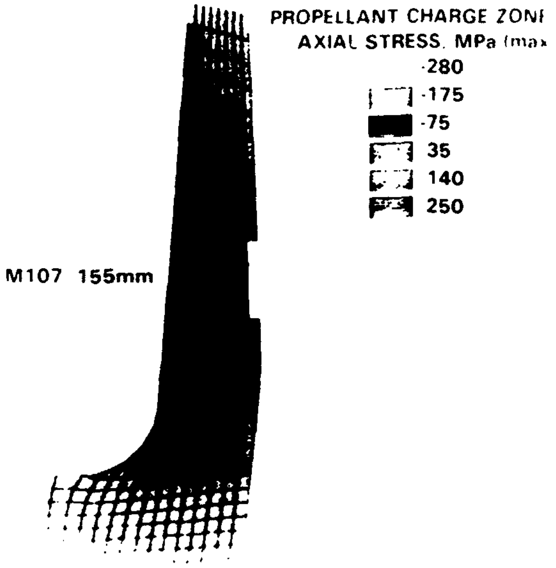


Figure 2. Axial stresses developed in the wall of an M107 artillery projectile on launch.

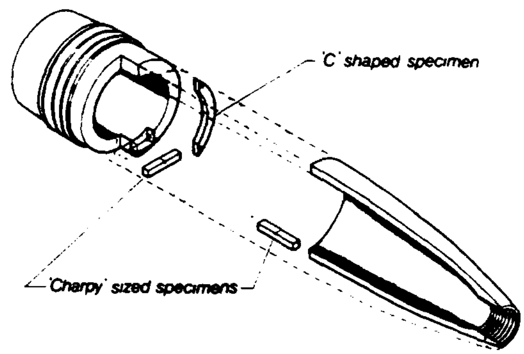


Figure 3. Fracture toughness specimens from an M795 155 mm projectile.

Table 2
Fracture toughness and critical crack[a] sizes in M107 155 mm projectiles.

Steel	Fracture toughness at -40 °C MPa$\sqrt{m}$	Fracture toughness at 21 °C MPa$\sqrt{m}$	Critical Crack Size at -40 °C mm	Critical Crack Size at 21 °C mm
HI-Frag (Isothermal heat treatment) σ_y = 620 MPa	20	25	0.86	1.35
HI-Frag (Quenched and tempered) σ_y = 980 MPa	33	47	2.4	4.5
STA64 (Quenched and tempered at max. tempering temp.) σ_y = 820 MPa	57	95	5.2	7.5
STA64 (Quenched and tempered at min. tempering temp.) σ_y = 1100 MPa	28	37	1.7	2.7

(a) external axial surface cracks, aspect ratio of 0.10 in a 12mm thick projectile wall; crack size is crack depth through the wall. Rough handling hoop stress of 350 MPa.

The fracture mechanics approach to assure launch safety does not usually account for the dynamic effects on fracture toughness. The tensile properties of many of these artillery projectile steels, however, have been characterised over a range of strain rates appropriate to projectile launch and generally these have been found to be only slightly influenced by strain rate over the range for projectile launch [1] and can be allowed for by using "dynamic safety factors" [12].

The use of carrier munitions would be expected to increase launch safety of large-calibre munitions since

higher toughness materials (steels) can be used in the casings. Despite recent developments in design, problems have been encountered in aluminium alloy base components and in the compressive failure of the bomblets themselves. Both of these problems have resulted in modifications to material and/or design.

The use of rocket motors in hand-held weapons systems may still be an area of concern with respect to launch safety, particularly with the continued use of light-weight alloy systems, such as 7000 series aluminium alloys [2] and maraging steels [13]. Both of these materials are used because of their high strength-to-weight ratios, but usually they have inherently low fracture toughness. In these weapon systems, the wall thickness of the rocket motor is usually so small as to preclude classical fracture mechanics approaches to assure launch safety, although an attempt has been made to apply fracture mechanics to low-toughness aluminium alloys in motors of moderate wall thickness [14] and maraging steel pressure vessels [15]. Typical fracture toughness data for aluminium alloys [2] and maraging steels are given in Tables 3 and 4 respectively. These data have been derived from small-scale fracture toughness tests and show the effects of composition and heat treatment on fracture toughness.

Launch safety of thin-walled rocket motor cases can be assured, at some cost, by alternative testing methods such as burst testing [16 - 19] and appropriate NDI methodologies such as eddy current inspection. In the area of pressure testing additional work on the effects of flaw size is required, but some experience has already been gained in the pressure testing of large calibre artillery projectiles [20].

New technologies to emerge in the launch of munitions have included the development of caseless ammunition, telescoped rounds, liquid propellants and, most recently, various electro-thermal propulsion technologies. The largest influence that these technologies can be expected to have on materials will be in the areas of gun barrel wear and erosion, as well as the possibility of hot gas erosion of projectile components (e.g., fins).

Despite the potential of these developments, there are still major problems to solve in making them cost effective and reliable within the constraints of size and weight demanded by current systems.

Table 3
Fracture toughness and critical crack[a] sizes in an aluminium alloy LAW motor case.

Al alloy	Fracture toughness at -40 °C MPa$\sqrt{m}$	Fracture toughness at 21 °C MPa$\sqrt{m}$	Critical Crack Size at -40 °C mm	Critical Crack Size at 21 °C mm
7001 - T6 σ_y = 555 MPa	-	17	not calculated	0.63
7278 - T6 σ_y = 540 MPa	18	18	0.79	0.79
7050 - T73 σ_y = 470 MPa	28	27	1.55	1.44
7475 - T73 σ_y = 480 MPa	-	32	not calculated	2.02

(a) internal axial surface crack, aspect ratio of 0.10 in a 4.6mm thick motor wall; operating stress = 354 MPa; crack size is crack depth through the wall.

Table 4
Fracture toughness and critical crack[a] sizes in a maraging steel rocket motor case.

Steel	Fracture toughness at -40 °C MPa$\sqrt{m}$	Fracture toughness at 21 °C MPa$\sqrt{m}$	Critical Crack Size at -40 °C mm	Critical Crack Size at 21 °C mm
Marage 200 σ_y = 1310 MPa	-	121	not calculated	(leak-before-burst)
Marage 250 σ_y = 1660 MPa	53	98	0.7	(2.4), (leak-before-burst)
Marage 300 σ_y = 2070 MPa	54	80 - 105	0.53	1.17 (on min. toughness)
Marage 350 σ_y = 2380 MPa	-	33	not calculated	0.17

(a) internal axial surface crack, aspect ratio of 0.5 in a 1.5 mm thick wall, 300 mm dia. motor; operating stress = 0.7 σ_y; crack size is crack depth through the wall.

4. FLIGHT DYNAMICS

The stresses imposed on relatively low velocity unguided munitions such as aircraft bombs and sub-munitions, during their flight to the target, may be small. However, high stresses and temperatures may be produced in munitions subjected to high velocities and/or accelerations due to manoeuvres. For example, the fins of high velocity KE penetrators are subjected to high temperature erosion and may require special coatings to maintain their integrity during flight.

Many first-generation missiles for anti-air or anti-ship applications have been designed to perform manoeuvres which generate relatively low "g" forces. This situation is changing rapidly with the emergence of highly manoeuvreable missiles for air and naval applications. New generation anti-ship missiles are expected to achieve velocities above Mach 2 and accelerations of typically 6 to 7 g during manoeuvres. This will require considerable improvements in the agility of the missiles designed to intercept this threat such as vertical-launch air defence missiles. Consequently, the stresses imposed on the casings and components of anti-missile missiles will rise considerably, and a continuing effort can be expected on both the materials and design aspects of such weapons.

5. TERMINAL EFFECTS

The functioning of ammunition at the target usually involves subjecting material to high transient loading. This may involve some or a combination of the following: (1) the detonation of a high explosive charge as in the case of EFPs, shaped charges and fragmentation weapons, (2) the interaction between the weapon and the target as in the case of KE penetrators, EFPs and metallic jets from shaped charges, (3) the interaction between the target material and the explosive shock wave as in the case of spallation weapons (HESH) and underwater explosive devices. Of particular interest, here, are cases (1) and (2), above. By way of example, Tables 5 and 6 (below) show some typical peak and average values for pressure, temperature and strain rate for projectile formation and target interaction problems for common ammunition [21]. These tables essentially demonstrate that the governing deformation conditions for typical munitions parts, can be at least 2 to 4 orders of magnitude above those seen in more conventional materials applications. Accordingly, great care must be taken to ensure that munitions design is based on materials properties which have been evaluated for the requisite range of dynamic loading conditions.

The basic requirements for optimum target penetration capability for a projectile are high velocity, high mass and small presented area. This requirement translates geometrically into a slender, high density, high velocity projectile with superior toughness and high stiffness to avoid premature failure at the target by fracture and/or bending. Penetration performance of armour piercing KE munitions can be met by a range of tungsten alloy and depleted uranium (DU) penetrators at current calibres. Whilst tungsten alloys can match DU performance at low L/D ratios, at high L/D ratios there is a consistent advantage to DU impacting monolithic steel armour at normal incidence [22]. Even if this differential in penetration performance could be contracted, the lower toughness of tungsten alloys compared with DU may still limit their performance against high obliquity targets. There is a benefit to be gained in using tungsten alloys because of the toxicity and radiation aspects of DU, provided the performance can be matched at a comparable cost. It appears that the L/D ratio for armour-piercing munitions has been increased to the limits of current launch and delivery technologies.

The extremes of strain, strain rate and temperature characteristics of the interaction of the of a penetrator with a metallic target are illustrated by the projectile deformation features shown in Figure 4 (below).

As shown in Figure 4, the recovered tungsten alloy projectiles show separation of the penetrator nose along a region of intense shear deformation, erosion features associated with mushrooming (deformation) and shear of the penetrator and features from the created surface show that melting temperatures have been exceeded. Whilst the average strain rate may be quite low ($\sim 10^3$ to $10^4\ s^{-1}$), local natural strains exceed the range 1 to 10 and local strain rates are often greater than $10^5 s^{-1}$.

Recent work has demonstrated that, within a specific velocity range, segmented penetrators out-perform continuous rod penetrators [23,24]. The contribution of spacers to the penetration performance needs to be separated from that of the penetrator segments because, in a real weapon, the spacers represent parasitic weight and are not altogether desirable. To fully utilise the advantages of segmented penetrators, the problems of the delivery of a segmented rod to the target at the required velocity need to be solved, and then a need for the enhanced penetration performance must provide the motivation for further development. Frank [25] has paraphrased the guiding philosophy for improving penetrator capability ...."bigger is better". This imposes a cost burden, not only for the individual munition, but also because of compliance with limitations of weapons system and platform constraints. The advent of electro-thermal propulsion technologies may change the concept of an axisymmetric penetrator as well as influence (probably for the better) the launch stress environment. Non - axisymmetric munitions will require significant changes to manufacturing technologies. The parasitic weight of sabots, which faciliate the launch of small diameter, high L/D penetrators in large diameter gun barrels, can be reduced by the use of higher strength metallic materials. It is also possible that metal matrix composite materials may be used, provided that reliable and safe launching can be guaranteed at a cost competitive with current technologies. Current sabot materials are acceptable but not optimal. If new penetrator technologies are adopted, however, this sabot technology will become obsolete.

Table 5
Projectile Formation Conditions

	Pressure GPa	Homologous Temperature[a]	Strain	Strain Rate s^{-1}
Shaped Charge Jet (3 to 10 km/s)	Peak ~ 200 Avg. ~ 20	Peak > 1 Avg. ~ 0.5 to 0.7	> 10	Peak ~ 10^6 to 10^7 Avg. ~ 10^4 to 10^5
Explosively Formed Penetrator (1.5 to 3 km/s)	Peak ~ 40 Avg. ~ 10	Peak ~ 0.5 to 0.8 Avg. ~ 0.2	Peak ~ 2 Avg. ~ 0.7	Peak ~ 10^6 to 10^7 Avg. ~ 10^4
Fragmentation (1.3 to 3 km/s)	Peak ~ 30 Avg. ~ 2	Ductile ~ 0.3 to 0.5 Brittle ~ 0.1	Ductile ~ 0.5 to 1.5 Brittle ~ 0.1 to 0.2	Peak ~ 10^6 to 10^7 Avg. ~ 10^4

(a) Temperature divided by melting temperature.

Table 6
Target Response Conditions

	Pressure GPa	Homologous Temperature[a]	Strain	Strain Rate s^{-1}
Gun Launched Ammunition (0.5 to 1.8 km/s)	Peak ~ 20 to 40 Avg. ~ 3 to 5	Peak ~ 1.0 Avg. ~ 0.3 - 0.5	Peak > 1.0	Peak ~ 10^6 to 10^7 Avg. ~ 10^4 to 10^5
Explosively Formed Penetrator (1.5 to 3 km/s)	Peak ~ 70 Avg. ~ 10	Peak ~ 1.0 Avg. ~ 0.2	Peak ~ 1 Avg. ~ 0.2 to 0.3	Peak ~ 10^6 Avg. ~ 10^4 to 10^5
Shaped-Charge Jet (3 to 10 km/s)	Peak ~ 100 to 200 Avg. ~ 10 to 20	Peak > 1.0 Avg. ~ 0.2 to 0.5	Peak >> 1.0 Avg. 0.1 to0 0.5	Peak ~ 10^6 to 10^7 Avg. ~ 10^4 to 10^5

(a) Temperature divided by melting temperature.

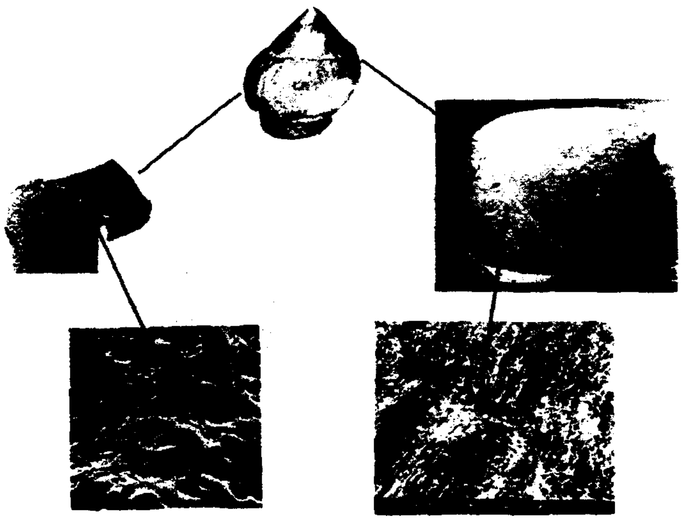


Figure 4. Deformation of tungsten alloy penetrator resulting from impact with armour steel plate.

For shaped charge and explosively formed projectile (EFP) weapons, a variety of projectile forming materials have been investigated including copper, iron, tantalum, DU, tungsten alloys and various super-plastic alloys. Parameters which influence the formation of, and subsequent stability and break-up of the penetrator, are generally well established (viz., formability, geometry, texture etc.). Extensive experimental work to obtain dynamic properties of candidate ammunition materials has been undertaken. As seen in Table 5 these materials may deform under strain rates as high as 10^4 s^{-1}. Quasi-static properties are no longer appropriate measures of the behaviour of these materials. Figure 5 shows the stress-strain behaviour of OFHC copper over a range of strain rates.

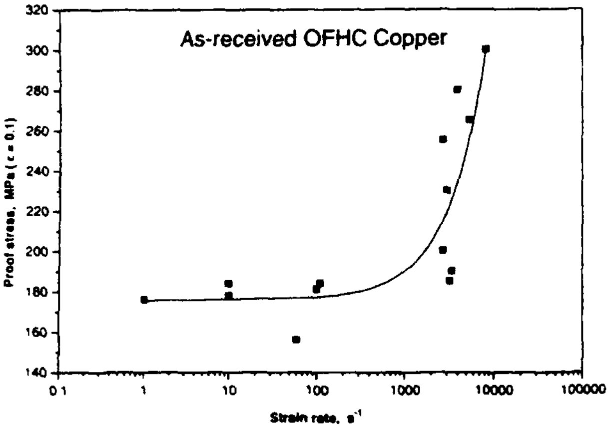


Figure 5. Effect of strain rate on the compressive proof stress of OFHC copper, [26].

Characterization of materials at high strain rates for EFP and other devices is essential otherwise the sometimes poor or unexpected dynamic response of arbitrarily selected materials may limit the performance of munitions. Since munitions design is still basically empirical some of the fully characterised candidate materials have not found general application. The properties of materials determined under conditions of high strain can be incorporated into computer codes (discussed below) for the modelling of explosively formed projectiles, projectile/target interaction and deformation of projectiles during launch.

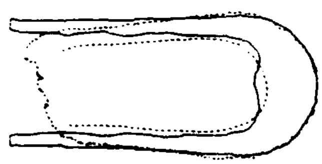
The principal new technology in munitions development has been the development of "dual charge" warheads for the defeat of explosive reactive (ERA) armour. Continuing developments can be expected as armour designers modify their ERA designs to render them more effective against "dual charge" warheads. A futher growth area has been the development of more effective EFPs particularly "fin-stabilised" EFPs for the top-attack of armoured vehicles. Significant progress has been made in this area particularly in the development of Armco® iron penetrators. However, considerable further development can be expected as this threat is countered by the designers of armoured vehicles.

Some munitions such as underwater mines produce their terminal effect solely by blast. More usually, high explosive (HE) warheads employ blast and fragmentation effects synergistically to optimise their effects on targets. Significant developments in this area have included HE artillery projectiles incorporating the "hi-frag" steels AISI 9260, STA-64 and HF-1 to optimise effectiveness against soft targets [27,28]. A further refinement has been the development of carrier or improved conventional munitions (ICMs) which dispense small bomblets over a wide area, and thus have improved effectiveness against dispersed infantry and (to a lesser extent) armoured targets. Emerging technologies include the incorporation of dense metal (primarily tungsten alloy) fragments into blast/fragmentation warheads to improve terminal effectiveness against high value-targets such as anti-ship missiles. In addition, further effort can be expected in the development of "reactive-cased" warheads in which a refractory metal liner is incorporated within the munition casing to improve its blast performance.

6. DESIGN AND MANUFACTURE OF MUNITIONS

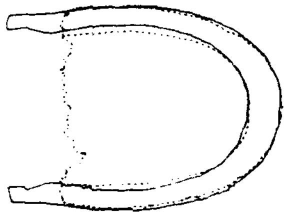
In addition to munitions performance requirements, producibility and cost effectiveness should also have a significant influence on materials selection. The design of munitions and other explosive devices is usually undertaken by engineering and explosive specialists, and the choice of materials is often based on "what is on the shelf". This means that the feasible optimum performance is not necessarily achieved because of inappropriate choice of materials and difficulties in production. Further, inappropriate choice of materials can lead to increased item costs arising from fabrication difficulties and, possibly, changes in design. It is essential, therefore, that candidate materials for munitions applications be well characterised in the area of producibility as well as in dynamic properties and terminal performance. One significant deficiency in dynamic property determination is the measurement of fracture toughness at high loading rates. At extremely high loading rates the measured toughness levels become highly sensitive to stress wave interactions within the specimens.

The use of finite element and finite difference computer codes as predictive tools for munitions undergoing deformation at high strain rate, typically 10^3 to 10^6 s^{-1}, is still in its infancy. Although finite element analysis (FEA) can contribute to basic understanding of these deformation processes they are not sufficiently mature to allow detailed design of weapons without extensive experimental testing. This situation arises from several factors including the inherent mathematical limitations of the physical model as well as the simplified description of materials behaviour for the defined loading conditions. For complex materials interaction problems, consititutive descriptions of materials and their deformation behaviour (particularly at high strain rates) are very limited. This limitation requires that for most ammunition design work the materials dynamic properties and constitutive relationships must be determined exactly, and often at great cost, for their confident application in munitions design. Nevertheless, the ability of the computer codes to elucidate the mechanics of deformation and to separate influences of parameters which cannot be easily studied or measured experimentally has been widely demonstrated [26,29]. This is illustrated in Figure 6 for fully formed copper and iron EFPs.



Time=[illegible] μs
Velocity=1.76 km/s

(a)



Time=250 μs
Velocity=1.81 km/s

(b)

Figure 6. Comparison of experimental ··············· and FEA ——— predicted EFP cross sections for (a) OFHC copper and (b) Remco® iron.

In Figure 6 the external and internal profiles of the fully formed projectiles were taken from X-ray negatives (dotted outlines) and the predicted shapes were produced by the ZEUS FEA modelling code[30] (solid outlines) using compression flow stress/strain data acquired from shocked material. These results generally show good agreement. However, these comparisons still demonstrate some obvious problems with excessive early folding of the EFP tail as well as overall head shape and dimensions.

Obtaining the maximum performance from a weapon system can then delay the necessity to introduce a new or modified weapon system with all attendant costs. Similarly, improved engineering design and manufacturing may decrease the immediate need for improved materials (e.g., increased precision of the weapon guaranteeing functioning close to the target). Ultimately, however, maintaining the effectiveness of any weapon system requires continued attention to all aspects of weapons design and manufacture as the target hardness is also adapted to counter weapon performance. New materials with improved dynamic properties are one key to the maximization of ammunition performance.

The introduction of new materials in ammunition design to maximise the several aspects of performance requires that their dynamic properties, as well as their quasi-static properties, are well characterized. This may be achieved by using extensive testing programs or a limited testing program in conjunction with computer modelling of material response to dynamic loading. During the design stage of ammunition development, due consideration must be given to each phase of the munitions cycle.

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